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HIGH TOUGHNESS PLATE ALLOY FOR AEROSPACE APPLICATIONS

Related Applications

This application claims the benefit of U.S. Provisional Application No. 60/069,591, filed December 12, 1997.

Field of the Invention

This invention is directed to the use of 2000 series alloy plate to be used for wing and structural intermediaries for aerospace applications.

Background of the Invention

The demands put on aluminum alloys have become more and more rigorous with each new series of airplane manufactured by the aerospace industry. The push is to provide aluminum alloys that are stronger and tougher than the generation of alloys before so that the aircraft industry may reduce the mass of the airplanes it builds to extend the flight range, and to realize savings in fuel, engine requirements, and other economies that can be achieved by a lighter airplane. The quest, no doubt, is to provide the aircraft industry with a high toughness and high strength aluminum alloy that is lighter than air.

U.S. Patent 5,213,639 is directed to an invention which provides a 2000 series alloy which provides an aluminum product with improved levels of toughness and fatigue crack growth resistance at good strength levels. As is fully explained in that patent, which is herein incorporated by reference, there are often trade-offs in the

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treatment of an aluminum alloy in which it is difficult not to compromise one property in order to increase another by some alteration to the process for the manufacture of the alloy. For example, by changing the heat treatment or aging of the alloy to increase the strength, the toughness levels may decrease. The ultimate desire to those skilled in the aluminum alloy art is to be able to change one property without decreasing some other property and, thereby, making the alloy less desirable for its intended purpose.

Fracture sensitive properties in structural aerospace products, such as fracture toughness, fatigue initiation resistance, and resistance to the growth of fatigue cracks, are adversely affected by the presence of second phase constituents. This is related to the stresses which result from the load during service that are concentrated at these second phase constituents or particles. While certain aerospace alloys have incorporated the use of higher purity base metals to enhance the fracture sensitive properties, their property characteristics still fall short of the desired values, particularly fracture toughness, such as in the 2324-T39 lower wing skin plate alloy, which is considered a standard in the aerospace industry. This goes to demonstrate that the use of high purity base metal by itself is insufficient to provide the maximum fracture and fatigue resistance in the alloy.

The invention hereof provides an increase in properties selected from the group consisting of plane strain and plane stress fracture toughness, an increase in fatigue life, and an increase in fatigue crack growth resistance and combinations thereof. These are all desirable properties in an aerospace alloy. In the practice of this invention the

alloy incorporates a balanced composition control strategy by the use of the maximum heat treating temperature while avoiding the incipient melting of the alloy. The use of high purity base metal and a systematic calculation from empirically derived equations is implemented to determine the optimum level of major alloying elements. Accordingly, the overall volume fraction of constituents derived from iron and silicon as well as from the major alloying elements copper and magnesium are kept below a certain threshold composition.

Increasing the above properties across the board allows the aerospace industry to design their planes differently since these properties will be consistently obtained under the practice of this invention. The present inventive alloys will be found useful for the manufacture of passenger and freight airplanes and will be particularly useful as structural components in aerospace products that bear tensile loads in service such as in the lower wing.

Summary of the Invention

The present invention is directed to the 2000 series composition aluminum alloys as defined by the Aluminum Association wherein the composition comprises in weight percent about 3.60 to 4.25 copper, about 1.00 to 1.60 magnesium, about 0.30 to 0.80 manganese, no greater than 0.05 silicon, no greater than 0.07 iron, no greater than 0.06 titanium, no greater than 0.002 beryllium, the remainder aluminum and incidental elements and impurities. Preferably, the composition comprises in weight percent 3.85 to 4.05 copper, 1.25 to 1.45 magnesium, 0.55 to 0.65 manganese, no greater than 0.04

silicon, no greater than 0.05 iron, no greater than 0.04 titanium, no greater than 0.002 beryllium, the remainder aluminum and incidental elements and impurities. When citing a range of the alloy composition, the range includes all intermediate weight percent's such as for magnesium, 1.00 would include 1.01 or 1.001 on up through and including 1.601 up to 1.649. This incremental disclosure includes each component of the present alloy. A preferred Cu_{target} composition is about 4.05 to about 4.28 companion to a Mg_{target} composition of about 1.25 to about 1.40 all in weight percent with the remaining constituents the same as in the before stated composition.

In the practice of the invention, the heat treating temperature, T_{max}, should be controlled at as high a temperature as possible while still being safely below the lowest incipient melting temperature of the alloy, which is about 935°F (502°C). The observed improvements is selected from the group consisting of plain strain and plane stress fracture toughness, fatigue resistance, and fatigue crack growth resistance, and combinations thereof while essentially maintaining the strength, is accomplished by ensuring that the second phase particles derived from Fe and Si and those derived from Cu and/or Mg are substantially eliminated by composition control and during the heat treatment. The Fe bearing second phase particles are minimized by using high purity base metal with low Fe content. While it is desirable to have no Fe and Si at all, but for the commercial cost thereof, a low Fe and Si content according to the preferred composition range described hereinabove is acceptable for the purposes of the present invention.

The fracture toughness of an alloy is a measure of its resistance to rapid fracture with a preexisting crack or crack-like flaw present. The plane strain fracture toughness, KIc, is a measure of the fracture toughness of thick plate sections having a stress state which is predominantly plane strain. The apparent fracture toughness, K_{app}, is a measure of fracture toughness of thinner sections having a stress state which is predominately plane stress or a mixture of plane stress and plane strain. The inventive alloy can sustain a larger crack than the comparative alloy 2324-T39 in both thick and thin sections without failing by rapid fracture. Alternatively, the inventive alloy can tolerate the same crack size at a higher operating stress than 2324-T39 without failure.

One way in which the improvements observed in the inventive alloy can be utilized by aircraft manufacturers is to reduce operating costs and aircraft downtime by increasing inspection intervals. The number of flight cycles to the initial or threshold inspection for a component depends primarily on the fatigue initiation resistance of an alloy and the fatigue crack propagation resistance at low ΔK, stress intensity factor range. The inventive alloy exhibits improvements relative to 2324-T39 in both properties which may allow the threshold inspection interval to be increased. The number of flight cycles at which the inspection must be repeated, or the repeat inspection interval, primarily depends on fatigue crack propagation resistance of an alloy at medium to high ΔK and the critical crack length which is determined by its fracture toughness. Once again, the inventive alloy exhibits improvements relative to 2324-T39 in both properties allowing for repeat inspection intervals to be increased.

An additional way in which the aircraft manufacturers can utilize the improvements in the inventive alloy is to increase operating stress and reduce aircraft weight while maintaining the same inspection interval. The reduced weight may result in greater fuel efficiency, greater cargo and passenger capacity and/or greater aircraft range.

Brief Description of the Drawings

Figure 1 shows a comparison of 2324-T39 plate with the properties of the inventive alloy.

Figure 2 shows the S/N fatigue resistance improvement of the inventive alloy as compared with the 2324-T39 alloy as maximum stress is plotted versus cycles to failure.

Figure 3 shows the increase in fatigue crack growth resistance of the inventive alloy as illustrated by the plot of da/dN versus ΔK.

Figure 4 shows a plot of yield strength versus K_{app} fracture toughness.

Figure 5 is a phase diagram showing isothermal section plots of the Al-Cu-Mg system for the temperatures 910°, 920°, and 930°F.

Detailed Description

Figure 5 shows calculated isothermal section plots of the Al-Cu-Mg system for the temperatures 910°F (488°C), 920°F (493°C), and 930°F (498°C). Of these, only the 930°F plot displays all the phase boundaries. The other phase boundaries have been omitted from the other isothermal lines for clarity and to better understand how the compositions of the 2000 series aluminum alloys were derived. The isothermal section

shows the different phase fields that coexist at different temperatures and compositions of interest in this alloy system.

For example, for the 930°F isothermal section, the composition regions of Mg and Cu are divided into four phase fields. These are the single phase aluminum matrix field (Al) bounded by the lines a and b to the left; the two-phase field consisting of Al and S (Al_2CuMg) bounded by the lines a and c; the two-phase field consisting of Al and θ (Al_2Cu) bounded by the lines b and d; and the three-phase field consisting of Al, S and θ bounded by the lines c and d.

These diagrams help to define a composition box or limitations of Cu and Mg and the ideal solution heat treatment (SHT) temperatures for an alloy composition that is positioned inside the single phase field of the Al matrix. Figure 5 also shows that the Al single phase field shrinks progressively with respect to the Cu and Mg compositions as the temperature is lowered, as compared to 920° and 910°F phase boundaries. This indicates that the solubility of the elements may be increased by treating the alloy at higher temperatures.

As recited above, it is important to confine the inventive compositions within the defined limitations of the isothermal plots so as to be inside the aluminum matrix single phase field. The compositions as shown in these plots are defined as effective compositions. The target compositions that make up the actual alloy can differ from the effective compositions since, at higher temperatures, a portion of the elemental composition of Cu is available to react with Fe and Mn and a portion of the elemental

composition of Mg is available to react with Si, which are then not available for the intended alloying purposes. These amounts are to be made up by requisite extra additions to the effective composition levels required by the equilibrium diagram considerations as in the isothermal plots of Figure 5. For example, in reference to Figure 5, the highest Cu for 1.45 Mg weight percent that remains within the single phase field at T_{max} of 925°F is a weight percent of 3.42 for Cu. This is defined as the effective Cu, or Cu_{eff}, which will be the Cu available to alloy with Mg for strengthening. To account for the part of Cu that will be lost through reaction with Fe and Mn, the total Cu or Cu_{target}, required is calculated from the following expression:

$$Cu_{target} = Cu_{eff} + 0.74(Mn - 0.2) + 2.28(Fe - 0.005)$$

$$Cu_{target} = 3.42 + 0.40 = 3.82$$

Note: This is for an Fe level of 0.05 and Mn = 0.60

It is observed that a Cu_{target} = 3.85 weight percent is obtained at a T_{max} = 925° F. Accordingly, the overall composition target for this example at a 925°F heat treatment is in weight percent: 0.02 Si, 0.05 Fe, 3.85 Cu, 1.45 Mg, 0.60 Mn, the remainder Al and incidental elements and impurities. This defines the "W" corner of the composition box in Figure 5.

As a second example, choosing a different Mg_{target} of 1.35 weight percent and a T_{max} equal to 920°F, the corresponding composition target is, in weight percent: 0.02 Si, 0.05 Fe, 3.92 Cu, 1.35 Mg, 0.60 Mn, the remainder Al and incidental elements and impurities. This defines the composition near the center of the composition box as a

preferred target composition.

Just as a Mg_{target} weight percent can be chosen to find the appropriate Cu_{target}, it is possible to work such a determination in reverse, by choosing a Cu_{target} to determine the amount of maximum Mg provided to the alloy composition. In this manner, a composition box for the preferred Cu and Mg combinations can be prepared for the cases with the maximum constant weight percents of 0.05 of Fe, 0.02 of Si and 0.6 of Mn. This has been superimposed on the Figure as the square box, defined by points W, X, Y, and Z. This composition box has a range of SHT temperatures between about 910° to 930°F.

Alloys within the W, X, Y, and Z box for a given SHT temperature can be selected so that little or no second phase particles should be present in the final alloy product.

To a certain extent, the above recited box can breathe. What is meant by this is that a small amount of boundary expansion can be effected by a decrease in the amount of silicon present, such as at less than 0.02, 0.03, or 0.04 weight percent. It is believed, although the inventors hereof do not want to be held to this belief, that by decreasing silicon to such minute levels, magnesium silicide as a reaction product is made in a de minimus amount or simply this reaction product is substantially inhibited. When this occurs, the incipient melting temperature increases above the lowest normal incipient melting temperature. That temperature increase allows a corresponding increase in solute concentration that will positively increase the important properties herein discussed. As a

result of this decrease in the magnesium silicide reaction product, an increase in the maximum temperature attainable can be realized. The maximum temperature may be increased by about 1, 2, 3, 4, or 5°F. When this occurs, the box W, X, Y, Z expands beyond its boundaries by the above 1° to 5°F temperature range.

By defining the composition limits by this iterative method, it was possible, upon appropriate processing, to achieve the desired strength goals. What is surprising, however, is that significant improvements in both fracture toughness and fatigue properties were also obtained without any strength compromise which have not been heretofore observed for this alloy group. Generally, when adjusting the composition of aluminum alloys as those skilled in this art appreciate, when one property gains, the usual circumstance is that another property suffers. Such is not the case under the present invention.

Figure 1 provides a summary comparison of the properties of 2324-T39 to that of the present invention. It is noteworthy that KIc, a measure of the plane strain fracture toughness, improved by 21.6 percent, K_{app}, a measure of the plane stress fracture toughness, improved by 9.2 percent, S/N fatigue resistance improved by 7.7 percent and the fatigue crack growth rate decreased by 12.3 percent, a decrease in this last property defined as an improvement, all over the analogous properties of 2324-T39 alloy. None of the other properties were decreased in the inventive alloy yet significant increases are noted in four primary properties. In any event, in the invention hereof, the minimum improvement observed in each of the properties is over 5% or over 5.5% preferably over

6% or 6.5% and most preferably over 7% or even 7.5%, of 2324-T39 as a standard prior art alloy, while maintaining an essentially constant high level yield strength at the same temper.

Figure 4 is a plot of K_{app} fracture toughness versus yield strength. This is a measure of the fracture toughness for thin sections of alloy. The inventive alloy shows a marked increase fracture toughness over the comparison alloy without a negative effect on the yield strength. It is noticed that the sample batch of the inventive alloy appears to have established a higher band of properties for K_{app} fracture toughness for this family of alloys.

The S/N fatigue curves of the inventive alloy and 2324-T39 are shown in Figure 2. The S/N fatigue curve of an alloy is a measure of its resistance to the initiation or the formation of a fatigue crack versus the applied stress level. The S/N fatigue curves for the inventive alloy and the 2324-T39 indicate that at a given stress level, more applied load cycles are required to initiate a crack in the inventive alloy than in 2324-T39. Alternatively, the inventive alloy can be subjected to a higher operating stress while providing the same fatigue initiation resistance as 2324-T39.

The fatigue crack growth curves of the inventive alloy and 2324-T39 are shown in Figure 3. The fatigue crack growth curve of an alloy is a measure of its resistance to propagation of an existing fatigue crack in terms of crack growth rate or da/dN versus the applied load expressed in terms of the linear elastic stress intensity factor range or ΔK. A lower crack growth rate at a given applied ΔK indicates greater

resistance to fatigue crack propagation. The inventive alloy exhibits lower fatigue crack growth rates than 2324-T39 at a given applied ΔK in the lower and middle portions of the fatigue crack growth curve. This means that the number of applied load cycles needed to propagate a crack from a small initial crack or crack-like flaw to a critical crack length is greater in the inventive alloy than in 2324-T39. Alternatively, the inventive alloy can be subjected to a higher operating stress while providing the same resistance to fatigue crack propagation as 2324-T39.

One way in which the improvements observed in the inventive alloy can be utilized by aircraft manufacturers is to reduce operating costs and aircraft downtime by increasing inspection intervals. The number of flight cycles to the initial or threshold inspection for a component depends primarily on the fatigue initiation resistance of an alloy and the fatigue crack propagation resistance at low ΔK. The inventive alloy exhibits improvements relative to 2324-T39 in both properties which may allow the threshold inspection interval to be increased. For example, at low stress intensity factor range of $\Delta K = 5$ ksi$\sqrt{\text{in}}$, da/dN for 2324 is 1.76×10^{-7} in./cycle, while that for the inventive alloy is 1.26×10^{-7} in./cycle, representing a decrease in the crack growth rate of 28%. The number of flight cycles at which the inspection must be repeated, or the repeat inspection interval, primarily depends on fatigue crack propagation resistance of an alloy at medium to high ΔK and the critical crack length which is determined by its fracture toughness. Once again, the inventive alloy exhibits improvements relative to 2324-T39 in both properties possibly allowing for repeat inspection intervals to be increased. For

example, at medium stress intensity factor range of $\Delta K = 14.3$ ksi$\sqrt{in}$, the crack growth rate da/dN for 2324 is 1.39×10^{-5} in./cycle, and that for the inventive alloy is 9.37×10^{-6} in./cycle, representing a decrease in the crack growth rate of 33%.